ENGINEERING CASE LIBRARY

ECL 135A

PROBLEM OF THE PERVERSE PINION (A)

a case history in failure analysis
told from the viewpoint of a consultant

by

Charles O. Smith
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Late in March 1968, I was consulted relative to a series of failures in pinions in automotive starter motor drives. In this particular case, a number of pinions had failed sufficiently prematurely to cause the company considerable expenditure through warranty replacements (cost of about $50 for each replacement; including new pinion, mechanic's time, paper work, etc., not to mention customer good will—some pinions were failing after a few weeks use!).*

The pinion in question is shown in Exhibit A-l. This pinion was used to drive a large gear in a starter motor with intermittent loading being applied rather rapidly to the extent of being essentially impact loading on some occasions.

The material specified was AISI 8620 steel for which the Time-Temperature-Tranformation (TTT) diagram is shown in Exhibit A-2.

This same pinion had been used extensively in previous applications with very little difficulty. Its use in somewhat different circumstances (in conjunction with a more powerful engine) caused an unacceptably large number of failures.

Processing and Specifications

Material was received as cold-drawn bars about 20 ft. long with a diameter of 1.000 in. (+ 0.000, - 0.002) with a maximum surface seam of 0.010 in. Bar was sheared to "slugs" of 1 in. length as shown in Exhibit A-3a.

The slugs were normalized at 1310°F in a continuous belt furnace. Belt speed was 4.1 ft/hr with a total cycle of 10 hrs. Specifications permitted a maximum hardness of Rockwell 80B.

Slugs were phosphate coated followed by application of a soap lubricant. A cold heading and finish extrusion on a heavy press produced the shaped teeth as shown in Exhibit A-3b. A series of machining operations drilled a center hole, rough-finished the hub, and finished the rest of the pinion to final dimensions. All surfaces were copper plated to a minimum thickness of 0.00035 in. and a maximum of 0.001 in. The copper plate was turned off the hub outside diameter. This was followed by processing in a continuous belt carburizing furnace. The pinions had a total heat cycle of 7.5 hr. with a furnace temperature of 1650°F and a gas atmosphere. Specifications call for a total case depth of 0.035 - 0.045 in. and a minimum surface carbon content of 1.00%.

The copper plate is stripped in preparation for a second carburizing operation. This is similar to the first but with a furnace temperature of 1560°F. Baskets of pinions move automatically through the furnace into a quench tank (molton salt at 425°F or oil at 130°F) followed by a spray wash. The case depth on the hub (before grinding) should be 0.045 - 0.055 in. The tooth case (at pitch diameter) should be 0.018 - 0.024 in.

The quenched pinions are tempered by passing through a furnace at 350°F at a belt speed of 1.2 in/min for 2 hrs. at heat followed by air cooling. Specifications require a Rockwell hardness of 79-82A on the teeth. Tooth structure should have

* The name of the specific company has been withheld, upon request, due to the current politically sensitive (in Feb., 1969) cut-back on warranties and the investigations of the Hart Committee on automative repair costs.

tempered martensite on the case with a maximum of 10% retained austenite and a combination of martensite and fine pearlite in the core.

Grinding operations on the hub and on the inside diameter produce the finished pinion shown in Exhibit A-3c.

Observations

A number of new, unused, pinions were examined visually with a magnifying glass and at 20X. The drive side surface (Exhibit A-1) of many teeth had long "stringy" defects and general roughness to an even greater extent that shown along the top of the tooth in Exhibit A-4.

The tooth in Exhibit A-4 shows an extreme example of a surface imperfection on a tooth of an unused gear. This defect extended across the root surface and up the back side of the neighboring tooth. Two small chips were removed from the defect in the root surface. Magnetic particle inspection of this pinion indicated the presence of sub-surface cracks along the pitch line and at the root of the teeth.

Examination of a number of failed pinions revealed each had one or more teeth with similar failures. A typical one is shown in Exhibit A-5. This tooth was one of three on this pinion which failed in the same apparent manner. The second failed tooth appears in the lower part of Exhibit A-5. The third tooth is below the second one in the orientation shown. Exhibit A-6 shows the same fractured tooth from the top.

Obviously, the company was anxious to obtain a technical solution to a costly technical problem. In discussing the problem with the company's representative, I sensed that there was also a matter of a strong difference of opinion as to the source of the trouble (and responsibility therefore) between two (or possibly more) operating groups within the company and thus a report submitted by me might well function to a considerable extent as a referee.

Student Questions

1. Analyze the situation.
2. Assess and define the problem.
3. Consider whether or not the material is proper.
4. Consider whether or or not the specified processing and heat treatments are proper.
5. Is the major difficulty (or source of trouble) obvious to you at this point?
6. What steps would you take to get to the "root" of the problem and thus obtain a solution?

APPENDIX

BRIEF NOTES ON FAILURE ANALYSIS

Introduction

Failures in components occur in a very small percentage of the millions of tons of materials fabricated and in service, yet they are of great importance to user, fabricator, and supplier. Failure of only one piece, out of a large number fabricated, can lead to many difficulties including extensive and expensive lawsuits, particularly if serious personal injury or death results. It simply is not reasonable, however, in the normal context of engineering practice, to expect absolutely no failures (even if everything has been done properly) when large numbers of a given component are being produced. Since there is some variation in all processes, it is inevitable that a few will be relatively weak. This is commonly recongized in procurement agreements in which the supplier guarantees a maximum failure rate (perhaps not more than one per thousand or per ten thousand) at a price agreed to by both consumer and supplier. When failure rate exceeds the guaranteed maximum or when failure leads to a serious, even fatal, accident, it often becomes necessary to thoroughly examine the situation to fix responsibility.

Elements to Failure Analysis

When we consider the great variety of materials and the myriad ways they can be used, it hardly seems possible to make an orderly and logical presentation of such a broad and complex topic. Despite the complexity it is possible to regard four factors as paramount in failure analysis. These are:

1. Material selected
2. Design of component
3. Fabrication of component
4. Operational use of component

We often think of each of these separately but this can be misleading since each of the four is very much related to the others.

Material Selection

Selection of the proper material for a given application obviously requires rather extensive knowledge of materials. One can summarize the process as follows:

1. Carefully list the conditions of service and environment the product must endure (analysis or requirements);
2. List the responses needed to withstand the conditions and changes of conditions in service;
3. Compare the needed responses with the properties (read responses) of the more than 70,000 engineering materials available in today's materials spectrum;
4. Choose the material which gives the best match or represents the best compromise possible in light of common sense, experience and judgment.

Component Design

Component design extends in many directions. One obvious direction, for only one example, is determining the proper geometry of the component with proper regard for minimizing stress concentrations

at changes of section, reentrant angles, etc. This is obviously related to choice of material. If a very limited number of suitable materials is available then the possible sizes are also limited. On the other hand, there are sometimes size limitations which may eliminate a number of materials from consideration because they simply do not have sufficient strength in the particular environment.

A variety of design deficiencies is often encountered. The principal one is faulty stress analysis, primarily due to either overlooking or not giving sufficient attention to potential sources of stress concentration. Others are: failure to allow for fabrication and assembly variables; failure to consider effect of possible bending or torsion on components designed to carry tension or compression; failure to consider anisotropic properties (texture); selection of improper material or incompatible combinations of materials; and inadequate or missing specifications.

Related to component design is development of specifications to insure proper performance in service. Another aspect of design is the development of fabrication schedules. This includes (1) procedures for obtaining proper size and shape and (2) proper treatment procedures for obtaining properties to meet specifications. It should be obvious to us that these two are strongly related as a heat treatment may be necessary after one fabrication step before a following step may be taken.

Component Fabrication

It is entirely possible for proper material (of good quality as procured) to be incorporated into an excellent design and yet have an unacceptable component. This comes from a number of things which can be summarized as failure to follow fabrication schedules, resulting in a component which does not meet specifications. If inspection and quality control are not functioning properly, the producer is quite likely due for trouble.

Some fabrication deficiencies are: machining errors; poor quality welding or brazing; surface damage by defective tools; damage by careless use of tools; and inadequate cleaning after internal machining or welding. A number of deficiencies are often classified as defective material including: surface decarburization in steels; heat treating cracks; omission of a heat treatment; forging flaws; overheating during heat treatment; porosity or cracks from casting; and excessive non-metallic inclusions. While these can be classified as defective material, the deficiencies are normally due to errors or poor control during fabrication.

Operational Use

In many situations a component of good quality material is properly fabricated in an excellent design and meets all specifications. Despite this, a component often fails in service. Failure can usually be attributed to abnormal use or improper maintenance (or both).

Abnormal use implies usage of the component in circumstances outside the limits of the original design constraints. This includes: overload (e.g., overspeed in an engine or abnormally high voltage); a change in temperature (normally an increase implying a weakening, although temperature reduction can lead to brittle failure in certain alloys); a change in atmosphere to increased corrosion; and

uncontrollable events (e.g., a bird striking an aircraft).

Improper maintenance includes: inadequate inspection after installation; failure to replace damaged components; inadequate lubrication; use of inferior replacement parts; improper alternation of components; inferior welding during repairs; inadequate or excessive torque applied to fasteners; failure to replace all fasteners; inadequate cleanup after repairs; insufficient thread engagement; damage from misuse of tools; improper adjustment after repairs; and damage from misuse of inspection equipment. Many of these lead to what is effectively overload under the modified conditions.

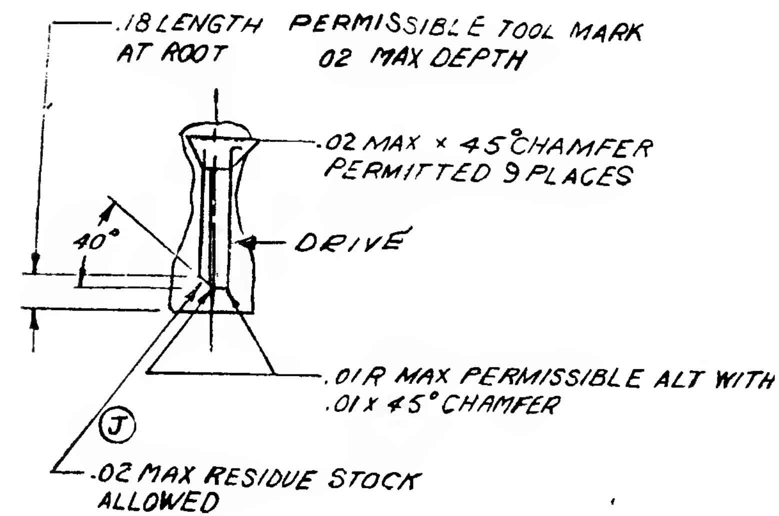
Summary Comment

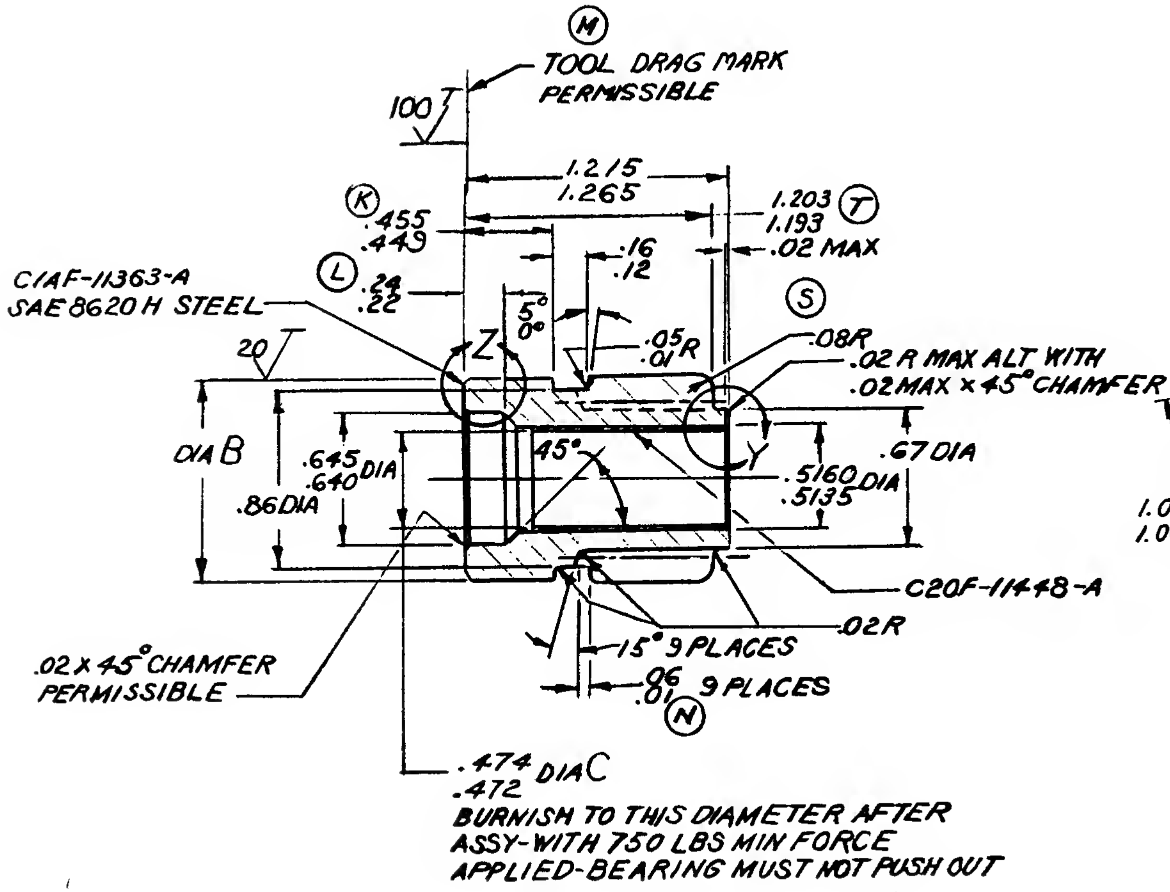
It should be obvious that analysis of failure and proper assignment of primary and secondary causes of failure is often a complex (and sometimes insoluable) problem. This is not said to discourage but to emphasize that care and caution are most important since the immediately obvious cause is not always the primary cause.

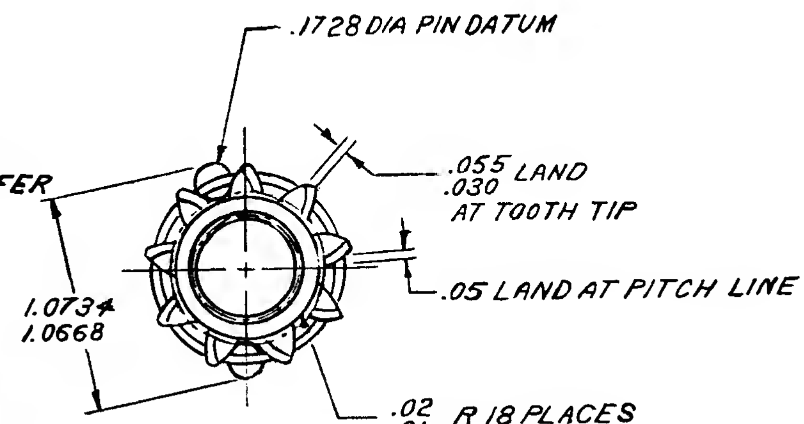
Despite all the possible sources of failure, fatigue is clearly the most common cause. The "beach mark" pattern which commonly identifies fatigue is not always apparent. High magnifications available in electron microscopy may reveal the crack front at each load cycle. Fatigue fractures in certain metals, such as hard steels, do not usually develop the beach mark pattern but may have a smooth area and a rough area which is typical of fatigue. Study of the pattern of the fracture surface often permits deduction of the point (and orientation of the stresses at the point) at which the failure started.

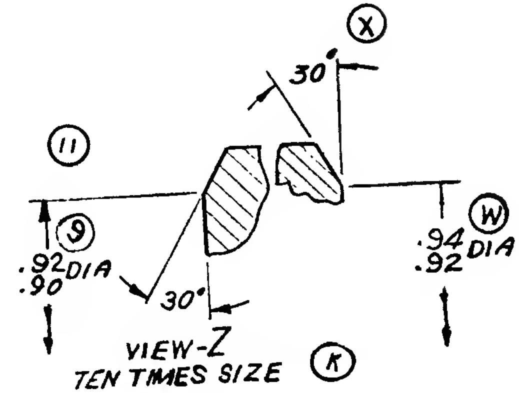
Exhibits, ECL 135A

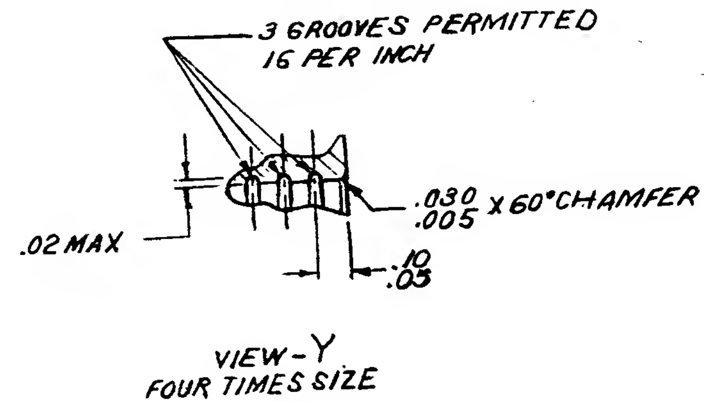
Exhibit A-1	Pinion with Nine Teeth
Exhibit A-2	Isothermal Transformation Diagram for AISI 8620 (C - 0.18, Mn - 0.79, Ni - 0.52, Cr - 0.56, Mo -0.19) asutenized at $1650^{o}F$
Exhibit A-3	Pinion in Various Stages of Processing
Exhibit A-4	A New Pinion
Exhibit A-5	Fracture of a Tooth Showing a Typical Fatigue Failure Starting at the Fillet in the Surface at 40^{o} to the End of the Pinion
Exhibit A-6	Same Fractured Surface as Shown in Exhibit 5 but Viewed from the Top


.18 LENGTH AT ROOT
PERMISSIBLE TOOL MARK .02 MAX DEPTH
.02 MAX × 45° CHAMFER PERMITTED 9 PLACES
40°
DRIVE
.01 R MAX PERMISSIBLE ALT WITH .01 × 45° CHAMFER
J
.02 MAX RESIDUE STOCK ALLOWED


M
TOOL DRAG MARK PERMISSIBLE
100
1.215
1.265
K
.455
.449
1.203
1.193
T
.02 MAX
.16
.12
L
.24
.22
C1AF-11363-A
SAE 8620 H STEEL
S
5°
0°
.05
.01 R
.08R
.02 R MAX ALT WITH
.02 MAX × 45° CHAMFER
20
Z
DIA B
.645
.640 DIA
45°
Y
.5160
.5135 DIA
.67 DIA
.86 DIA
C20F-11448-A
.02R
15° 9 PLACES
.06
.01 9 PLACES
N
.02 × 45° CHAMFER PERMISSIBLE
.474
.472 DIA C
BURNISH TO THIS DIAMETER AFTER
ASSY-WITH 750 LBS MIN FORCE
APPLIED-BEARING MUST NOT PUSH OUT


.1728 DIA PIN DATUM
.055
.030 LAND AT TOOTH TIP
.05 LAND AT PITCH LINE
1.0734
1.0668
.02
.01 R 18 PLACES





	GRADE	DIAMETER B
*	1	.986 - .985
	2	.984 - .983
	3	.982 - .981
	4	.980 - .979
	5	.978 - .977
	6	.976 - .975
*	7	.974 - .973
*	8	.972 - .971
*	9	.970 - .969
*	10	.968 - .967

G

GRADES MARKED THUS * ARE SALVAGE GRADES

P REMOVE ALL LOOSE CURLED BURRS-SEE ENGINEERING CONTROL SAMPLE

BEARING MUST BE FREE OF ABRASIVE PARTICLES

DIAMETER B MUST NOT HAVE OVER .001 TAPER PER INCH (H)

DIAMETER B MUST BE CONCENTRIC WITH DIAMETER C WITHIN .003 T/R

CASE HARDEN PER PROCESS SPEC HT4-1
.05 MAX TOTAL CASE DEPTH ON DIAMETER B
.03 MIN EFFECTIVE DEPTH ON DIAMETER B
.018 TO .024 TOTAL DEPTH OF CASE ON ALL SURFACES EXCEPT DIAMETER B
CORE ROCKWELL C32-44
Y CASE ROCKWELL A79-82 C56-61
RETAINED AUSTENITE IN CASE 10% MAX

ENGINEERING APPROVAL OF PRODUCTION SAMPLES FROM EACH SUPPLIER IS REQUIRED PRIOR TO AUTHORIZATION OF INITIAL PRODUCTION-FOR SAMPLE REQUIREMENTS SEE ENGINEERING RELEASE

ENGINEERING APPROVAL MUST BE OBTAINED BEFORE ANY CHANGE IN MATERIAL-CONSTRUCTION OR PROCESSING CAN BE MADE

FOR ENGINEERING APPROVED SOURCE SEE ENGINEERING RELEASE

PINION DATA

TEETH	9 (CUT ON 10.48 TOOTH BLANK)
PITCH	12/14 SPECIAL
PRESSURE ANGLE	12°
PITCH DIA	.750
BASE CIRCLE	.7336
TRUE INVOLUTE WITHIN .001 OUTSIDE .740 DIA	
ROOT DIA	.692 - .684
OUTSIDE DIA	1.0164 - 1.0114 (1.0164 THEOR)
TOOTH SPACING ERROR	
TOOTH TO TOOTH	.0005
CUMULATIVE	.002

PITCH DIA NOT OVER .005 RUNOUT WITH DIA C
OUTSIDE DIA NOT OVER .006 RUNOUT WITH DIA C

EXHIBIT A-1 PINION WITH NINE TEETH

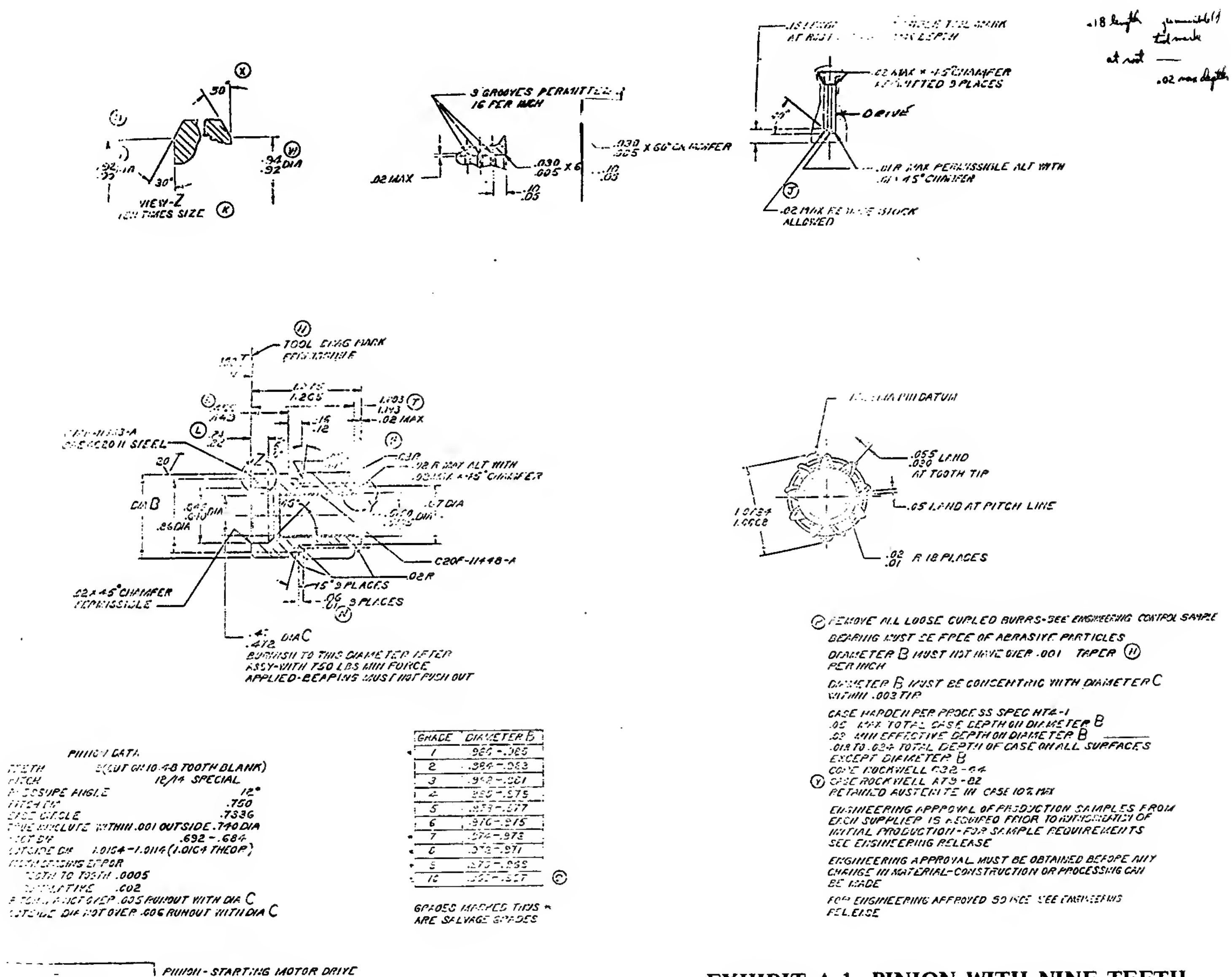
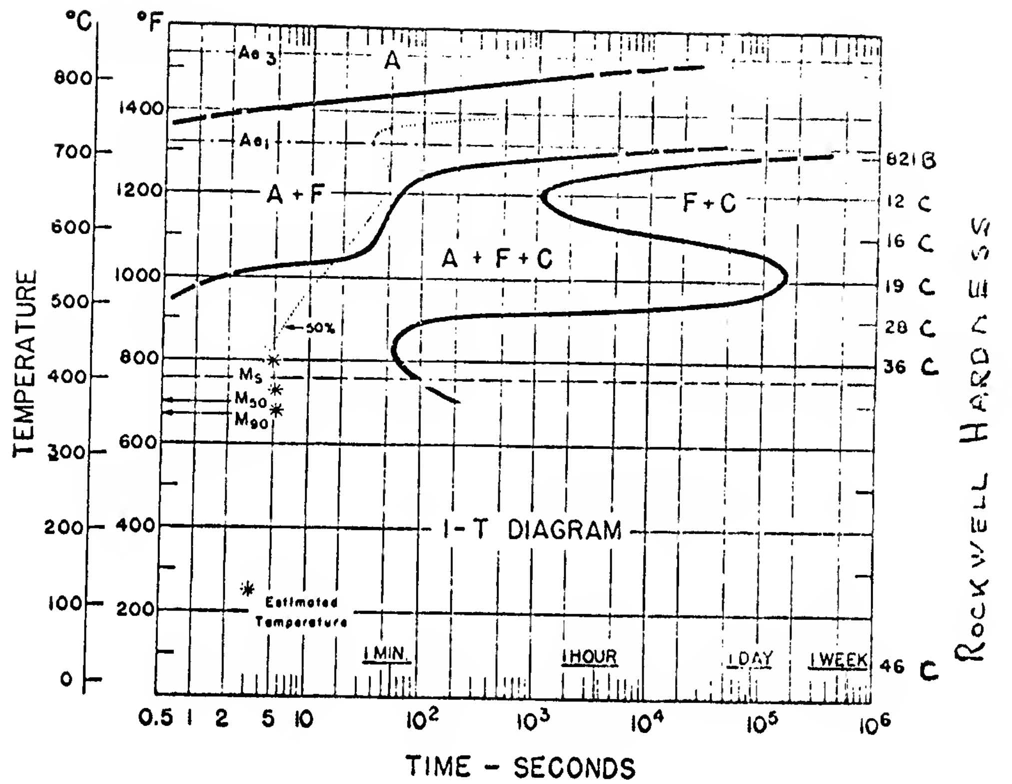


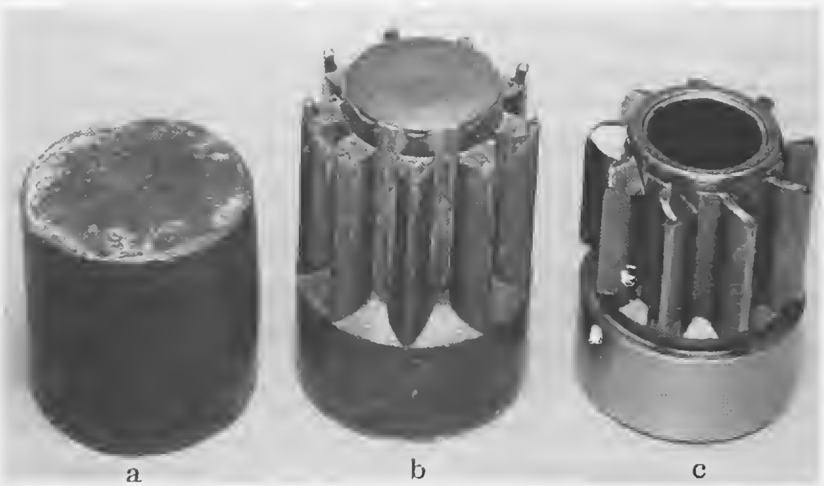
EXHIBIT A-1 PINION WITH NINE TEETH



Isothermal Transformation Diagram for AISI 8620
(C - 0.18, Mn - 0.79, Ni - 0.52, Cr - 0.56, Mo -0.19)
asutenized at 1650°F

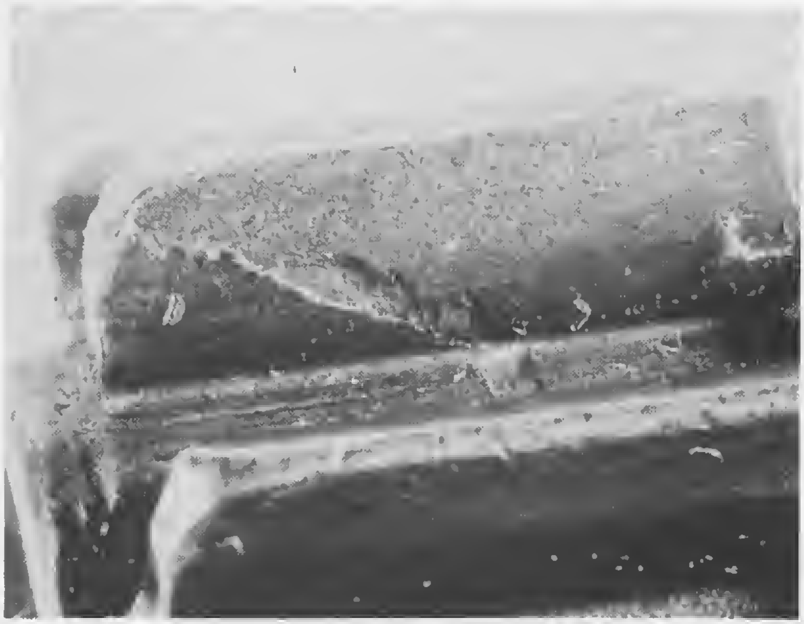
Legend A Austenite
B Ferrite
C Carbide

EXHIBIT A-2



Pinion in Various Stages of Processing.
(a) "Slug" as sheared from bar stock
(b) Slug after cold heading and extrusion to form teeth
(c) Finished pinion

EXHIBIT A-3



5x

A new pinion.
Defect (on drive side of tooth) extends across root surface and up the back side of the tooth in the foreground. Two small chips were removed from the defect at the root surface. Magnetic particle inspection indicated sub-surface cracks along the pitch line and at the fillet at the tooth root. Note general roughness and "strings" of small defects along the top of the surface of the tooth.

EXHIBIT A-4

5x

Fracture of a tooth. There is some suggestion of a "woody" mascrostructure in the failed surface. Visual examination at 20X with a binocular microscope gives an illusion of an undercut at the fillet.

Same fractured surface as shown in Exhibit A-5 but viewed from the top. The delineation of the "smooth" portion from the "rough" portion is quite distinct.

EXHIBIT A-6

ENGINEERING CASE LIBRARY

ECL 135B

PROBLEM OF THE PERVERSE PINION (B)

a case history in failure analysis
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The choice of AISI 8620 is entirely reasonable since it is quite possible to develop structures which will meet the stated specifications. It is true that a number of other steels can meet the specifications equally well but AISI 8620 is less expensive than most of the others. Spectrographic analysis confirmed the material was AISI 8620.

The normalizing operation specified a furnace temperature of 1310^{O}F. Examination of Exhibit A-2 indicates that this temperature is marginal. A metal temperature of 1325 to 1330^{O}F would appear to be better for insuring proper structure before cold forming the teeth. (There was no evidence, however, of specific difficulty or failure originating from this marginal temperature).

While the appearance of the tooth surface in Exhibit A-4 is an extreme example, the general roughness was found on many of the pinions examined, both new and used. This appearance is NOT typical of surfaces which have been cold worked and could be due to small surface seams in the original stock, dirty dies used in forming the teeth, and/or stripping the copper plate.

The dimensional tolerances shown in Exhibit A-1 seem reasonable. One critical dimension is not clearly stated. Observe the situation at the end of the tooth at the base of the surface which is at an angle of 40^{O} to the end of the pinion. It is not obvious that a fillet radius is stated although one could infer that it should be 0.01 to 0.02 in., i.e., the same as the fillet radius at the base of the pinion teeth.

The failed teeth shown in Exhibits A-5 and A-6 were typical of the failures on other pinions. These are characteristic fatigue failures. Failure was initiated in the fillet at the root of the machined surface which is at 40^{O} to the end of the pinion. There is a "smooth" portion adjoining this fillet which merges into a "rough" portion of the fracture at some distance from the fillet.

Exhibit B-1 is a section of this failure at the fillet. This is at the location for which the radius is not clearly specified (see comment on Exhibit A-1 above). If we assume that this raduis should be the same as at the root of the teeth (0.010 to 0.020 in.), it is obvious that the assumption is not justified in this case since the radius is approximately 0.002 in.

Exhibit B-2 shows a section on the drive (pressure) side of the failed tooth near the fracture. The presence of reformed martensite indicates high localized stress.

A Rockwell hardness of 80A (equivalent to Rockwell 58C) was measured on the hub. A diamond pyramid hardness of 730 (equivalent to Rockwell 61.50) was found at 0.003 in. below the surface at the pitch line. This is just slightly above the specification of Rockwell 79-82A (56-61C). The total case depth on the tooth is 0.022 in. and is thus within secpification limits. Tooth core structure is tempered (low carbon) martensite. The tooth case shows approximately 30-40% retained austenite to a depth of 0.006 in. (Exhibit B-3). This obviously exceeds the specification limit of 10%.

Summary and Conclusions of Analysis

The major factor leading to tooth failure was the high concentration of stress at the root of the surface at 40^{O} to the end of

the pinion. This has several contributory factors: stress concentration from the much-too-small fillet radius; increase in applied load above previous requirement; and probable existence of sub-surface cracks before use.

The general appearance of new pinions and failure to meet various specifications (e.g., Exhibit B-3) are, in this case, of secondary consideration although these, in the absence of the primary factor of high stress concentration, would lead to excessive wear and pitting along the wear surfaces. This in turn could result in fracture. These secondary aspects are difficult to reconcile with high quality work in which there has been proper control of processing and proper inspection.

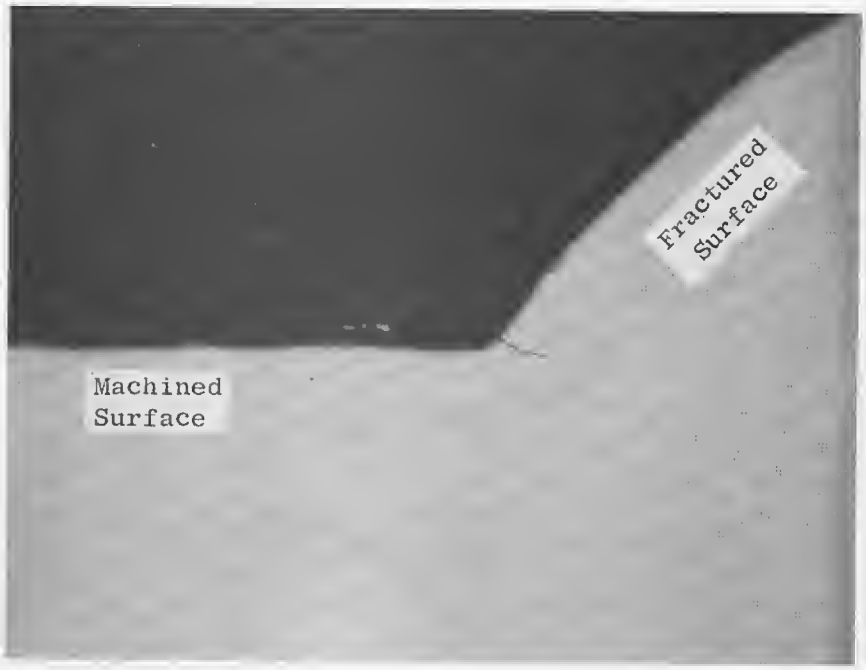
Further Comments

When the company's representative received the report and discussed it with me, his major comment was, "How could we have missed that?" I had no answer to that since fatigue failures initiating at a stress concentration, such as this failure, are all too common.

In February 1969, I checked with the company representative to see what developments, if any, had come from the investigation. He made it clear that there was no question about the technical solution. Despite this, however, no change had been made in the pinion (tooling costs, etc., associated with even a small design change are costly!). Even so, the warranty problem had receded to an acceptable level. This was accomplished by using the report as a form of pressure on the production people to "sharpen up." Proper design changes can be made later, at retooling time for new models, if needed.

Exhibits, ECL 135B

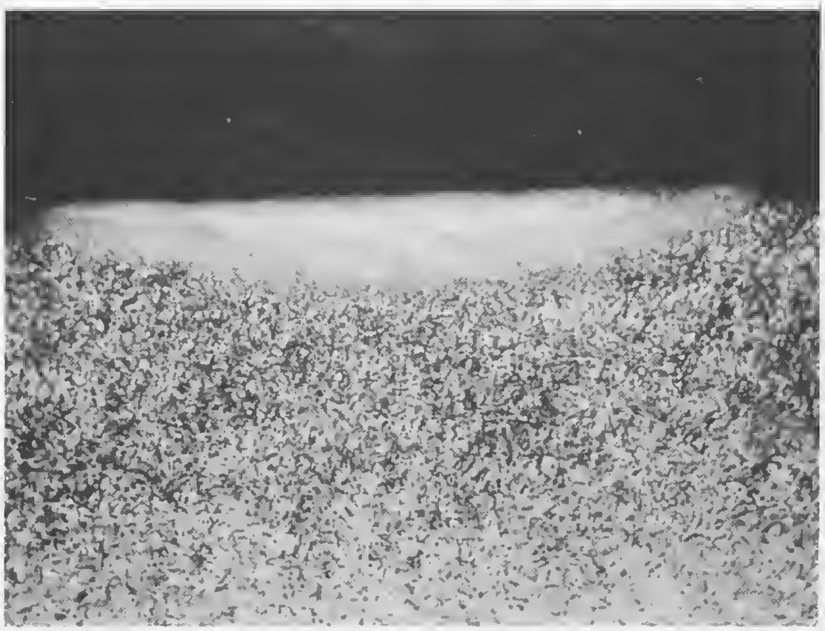
Exhibit B-1	Section Through Failed Tooth Through the 40° Surface
Exhibit B-2	Section on Drive (Pressure) Side of Failed Tooth Near the Fracture Showing Reformed Martensite, Indicating Heavy Localized Stress
Exhibit B-3	Carburized Case on Tooth Showing 30-40% Visible Retained Austenite to a Depth of 0.006 in.



As polished 100 x

Section through failed tooth through the 40^{o} surface. The measured radius of the fillet is approximately 0.002 in. A crack is apparent at the fillet.

EXHIBIT B-1



2% Nital 200x

Section on drive (pressure) side of failed tooth near the fracture showing reformed martensite, indicating heavy localized stress.

EXHIBIT B-2

2% Nital 500x

Carburized case on tooth showing 30-40% visible retained austenite to a depth of 0.006 in.

EXHIBIT B-3